Evaluation of Chamber Effects on Antenna Efficiency Measurements Using Non-reference Antenna Methods in Two Reverberation Chambers

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Abstract: In this paper, the evaluation of chamber effects on antenna efficiency measurements using non-reference antenna (NRA) methods is presented. Two reverberation chambers have been employed and they differ in dimensions and paddle stirrer configurations, therefore the corresponding electrical characteristics such as quality factors, decay constants, and enhanced backscatter coefficients are envisaged to be different. However it is found that these differences have little influence on the efficiency measurement of antennas-under-test (AUTs). The AUTs used for this study were a directional antenna and an omni-directional antenna. The discrepancy in the efficiency of the two antennas measured between the two chambers is less than 10% within their operational frequency bands. These results demonstrate that the non-reference antenna measurement techniques are robust. Further investigation shows that the directional antenna is slightly more prone to polarisation mismatch than the omni-directional antenna is. Therefore, polarisation stirring should be implemented when using the non-reference antenna methods for antenna efficiency measurement especially for directional antennas.

1. Introduction

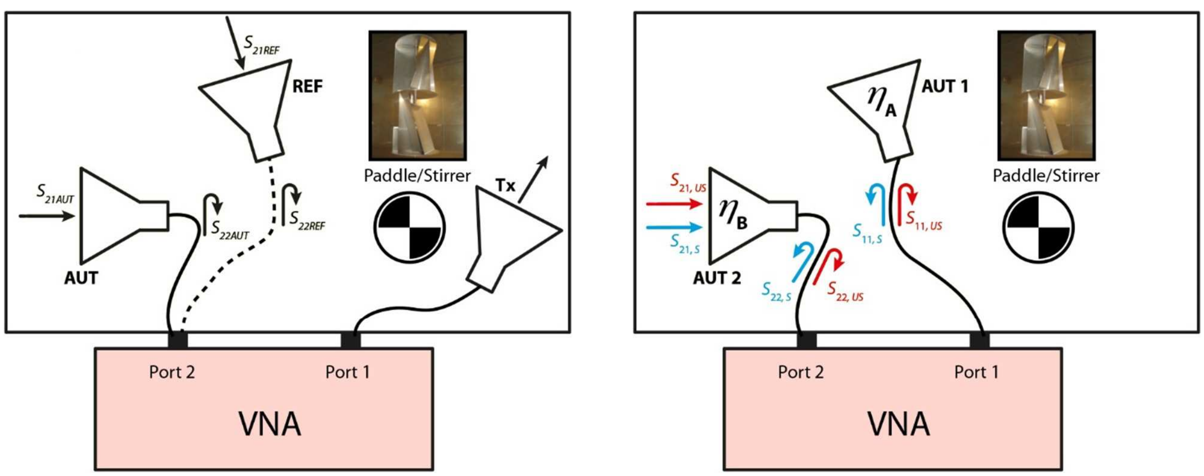
Antenna efficiency is one of the most important parameters for antenna design and applications, however accurately and effectively measuring it has been a challenge for many decades [1, 2]. The conventional way of obtaining the efficiency is to measure the maximum gain and maximum directivity of the antenna in an anechoic chamber and take a ratio of the former over the latter. There are several techniques to obtain antenna gain and directivity [1-3] and they require precise alignment between transmitting and receiving antennas which is usually time-consuming and expensive. Alternatively, other methods such as the Wheeler cap method [4-6] and reverberation chamber (RC) method [7-9], which do not require alignment, have been proposed. The Wheeler cap method is intrinsically band-limited and usually used for measuring electrically small antennas; on the other hand, the RC method has much broader applications.

RCs have become popular for antenna efficiency measurement due to their simplicity and easy setup implementation. A perfect RC provides a statistically homogeneous and isotropic field within the chamber working volume above the lowest usable frequency. This allows both transmitting and receiving antennas to be placed randomly in the working volume of the RC as long as they do not have line-of-sight propagation. This significantly reduces the setup complexity and therefore the cost. An RC generally consists of a metallic room/chamber and one or more metallic mode stirrer(s), usually in the form of a large paddle. The principle of operation of the RC is based on the existence of multimode resonance mixing [10], which can be achieved either by mode tuned or mode stirred methods. In this paper, we consider a mode tuned method in which the RC is stimulated with a CW signal and the stirrer is rotated between discrete positions. Continuous rotation of stirrer can also be used. It is not considered in this work as little difference between them has been found for EMC testing as long as the sampling rate for the continuous mode is large compared to the chamber's transient and system integration times [11]. At each position of the stirrer, frequency swept scattering parameters (*S*-parameters) are recorded after the paddles have stopped moving so that the data is always sampled in a steady state. The number of stirrer steps is defined such that the field are random enough to produce the desired feature. Due to the statistical nature of the RC, the larger the number of measurement samples the better the accuracy of the efficiency that can be achieved. These measurements are normally done using various stirring techniques such as frequency stirring, source stirring, polarisation stirring and paddle/mechanical stirring [9, 12].

In conventional method for measuring antenna efficiency in a RC, a reference antenna with known efficiency is required; hence we refer to it as the reference antenna (RA) method. Fig.1a schematically illustrates a typical test setup for this method. The transmitting antenna, designated as Tx, is set on the right of the paddle stirrer and the receiving antennas including a reference antenna, designated as REF, and an antenna-under-test, designated as AUT, are placed on the left of the paddle stirrer. Such an arrangement can minimise line-of-sight propagation between transmitting and receiving antennas. In order to obtain the efficiency of the AUT, two sets of *S*-parameter measurements over a number of paddle steps per revolution are required: one is the *S*-parameters between the transmitting antenna and the reference antenna, S_{REF}, and the other is the *S*-parameters between the transmitting antenna and the AUT, S_{AUT}. The measured *S*-parameters along with the known efficiency of the reference antenna are then used to calculate the efficiency [7-9]. The accuracy of the obtained efficiency is highly dependent on the accuracy of the efficiency of the reference antenna.

Recently, Holloway *et al.* [13, 14] have introduced new antenna efficiency measurement methods using an RC which do not require a reference antenna which means that only the AUTs are required. We will refer to these methods as non-reference antenna (NRA) methods that include one-antenna, two-antenna and three antenna methods. Fig. 1b illustrates the schematic measurement setup for the two-antenna NRA method. One can see that only AUTs are required in the RC and only a single set of *S*-parameter measurements is required to obtain the efficiency of the AUTs. Compared with the RA method, the NRA methods have simpler measurement setups; more importantly, the uncertainties that the reference antenna may introduce are removed. Uncertainties of the NRA methods have been analysed in [14] and correction of antenna impedance mismatch was discussed in [15]. Validation of the NRA methods on different types of antennas, their repeatability over time, the effect of antenna positions, and antenna proximity effects were also investigated [14, 16-18]. Although some initial results on comparing different RCs were given by us in [19], little analysis was given. Thus a further in-depth investigation has been conducted and in report this paper.

In this work, we have investigated how the difference between RCs impacts on the results of the NRA methods for antenna efficiency measurement. The NRA methods have been verified against the conventional antenna efficiency measurement method based on anechoic chambers in [13] but it is also important to verify robustness of these methods when using different RCs. To achieve that, we have carried out an inter-comparison on both directional and omnidirectional antennas between RCs at the UK National Physical Laboratory (NPL) and the University of Liverpool. We analysed the difference in electrical characteristics between the two RCs such as Q-factors, enhanced backscatter coefficients and decay constants and compared the antenna efficiency measured using two sub-categories of the NRA methods namely the one-antenna NRA method and the two-antenna NRA method [14]. We also studied how antenna polarisation could influence the implementation of the methods on directional and omni-directional antennas.



a b

Fig. 1 Illustration of efficiency measurement setups for the RA method and the two-antenna NRA method in RCs.
a RA method
b NRA method with two antennas

2. Theory

As depicted in Fig.1b, each measured complex S-parameter, $S_{ij}(n,f)$ (i, j ∈ {1,2}) consists of two parts: stirred $S_{ij,s}$ and unstirred $S_{ij,us}$ where f and n are frequency and paddle step, respectively. The two-port vector network analyser (VNA) is calibrated up-to the antenna feed ports. The stirred part is contributed from the reflected signals from the rotating paddle stirrer and the unstirred part is the reflection from the unmovable objects of the chamber such as walls, floor and ceiling and within the chamber such as antenna supports. The relationship between them is written as [14],

$$S_{ij}(n,f) = S_{ij,s}(n,f) + S_{ij,us}(f) \qquad (1a)$$

or

$$S_{ij,s}(n,f) = S_{ij}(n,f) - S_{ij,us}(f) \qquad (1b)$$

where

$$S_{ij,us}(f) = \left\langle S_{ij,s}(n,f) \right\rangle \qquad (2)$$

$\langle \bullet \rangle$ denotes ensemble average.

The NRA methods introduced in [14] are based on the theory that the Q-factor of a RC measured in the frequency-domain Q_{FD} is different from that measured in the time-domain Q_{TD} and the ratio of them is equal to the product of the total efficiency of the two antennas. This relationship is written as

$$\eta_A \eta_B = \frac{Q_{FD}}{Q_{TD}} \qquad (3a)$$

$$Q_{FD} = C_{RC} \left\langle \left| S_{21,s}(n,f) \right|^2 \right\rangle \qquad (3b)$$

$$Q_{TD} = \omega \tau_{RC} \qquad (3c)$$

where C_{RC} is the chamber constant of the RC at a certain wavelength λ and given as,

$$C_{RC} = \frac{16\pi^2 V}{\lambda^3} \qquad (4)$$

and V is the chamber volume. $\left\langle \left| S_{21,s} \right|^2 \right\rangle$ is the averaged received power and can be derived from (1b) and (2). ω is the angular frequency. τ_{RC} is the decay constant or the decay time of the chamber and can be calculated as follows.

Firstly, calculate the impulse response of the chamber $h(n,t)$ at each paddle position by computing the inverse Fourier transform (IFT) over a certain frequency range e.g. 100 MHz (note a rectangular window is used here).

$$h(n,t) = IFT\left[S_{ii}(n,f)\right],\ i \in \{1,2\} \qquad (5)$$

Secondly, derive the power delay profile (PDP) by taking the ensemble average of the $|h(n,t)|^2$ over all paddle positions

$$PDP\ (t) = \left\langle |h(n,t)|^2 \right\rangle \qquad (6)$$

Lastly, work out the decay constant τ_{RC} as follows

$$\tau_{RC} = -\left(\frac{1}{k}\right) \qquad (7)$$

where k is the slope of the straight line obtained by plotting $\ln(PDP\,(t))$ against t.

In the one-antenna NRA method when the same antenna is used as both the transmitting antenna and the receiving antenna, $\eta_A = \eta_B$, It is also assumed that the RC is well "stirred" or that a perfectly statistically uniform electromagnetic field is created inside the RC, therefore we have $Q_{FD} = \frac{1}{2} C_{RC} \left\langle |S_{11,s}(n,f)|^2 \right\rangle$. And the total efficiency of the antenna is derived as

$$\eta_A = \sqrt{\frac{C_{RC} \left\langle |S_{11,s}(n,f)|^2 \right\rangle}{2 \cdot \omega \cdot \tau_{RC}}} \qquad (8)$$

In the two-antenna NRA method, two antennas are used in the test and the assumption of the well "stirred" environment is no longer needed. It is more realistic to replace 2 in the denominator of (8) by the enhanced backscatter coefficient, e_b of the RC, which can be used to estimate how well a RC is stirred and is given as,

$$e_b = \frac{\sqrt{\left\langle |S_{11,s}(n,f)|^2 \right\rangle \left\langle |S_{22,s}(n,f)|^2 \right\rangle}}{\left\langle |S_{21,s}(n,f)|^2 \right\rangle} \qquad (9)$$

Thus, the total antenna efficiency for both antennas are derived within a single set of S-parameter measurement and the equations are given as

$$\eta_A = \sqrt{\frac{C_{RC} \left\langle |S_{11,s}(n,f)|^2 \right\rangle}{e_b \cdot \omega \cdot \tau_{RC}}} \qquad (10a)$$

$$\eta_B = \sqrt{\frac{C_{RC} \left\langle |S_{22,s}(n,f)|^2 \right\rangle}{e_b \cdot \omega \cdot \tau_{RC}}} \qquad (10b)$$

When considering the radiation efficiency, the antenna mismatches must be corrected. $\left\langle \left| S_{11,s}(n,f) \right|^2 \right\rangle$ in (8) and (10a) and $\left\langle \left| S_{22,s}(n,f) \right|^2 \right\rangle$ in (10b) have to be replaced by $\left\langle \left| S_{11,s}(n,f) \right|^2 \right\rangle_c$ and $\left\langle \left| S_{22,s}(n,f) \right|^2 \right\rangle_c$, respectively as below

$$\left\langle \left| S_{11,s}(n,f) \right|^2 \right\rangle_c = \frac{\left\langle \left| S_{11,s}(n,f) \right|^2 \right\rangle}{\left(1 - \left| \left\langle S_{11,s}(n,f) \right\rangle \right|^2 \right)^2} \tag{11a}$$

$$\left\langle \left| S_{22,s}(n,f) \right|^2 \right\rangle_c = \frac{\left\langle \left| S_{22,s}(n,f) \right|^2 \right\rangle}{\left(1 - \left| \left\langle S_{22,s}(n,f) \right\rangle \right|^2 \right)^2} \tag{11b}$$

3. Measurement setups and results

Fig. 2a and Fig. 2b show photos of the actual measurement setups inside the two chambers. The RC at NPL has dimensions of 6.55 m × 5.85 m × 3.5 m and the RC at University of Liverpool has dimensions of 3.6 m × 4 m × 5.8 m. The former has only one vertically installed paddle stirrer but the latter has two paddle stirrers (one is vertical and the other is horizontal). The total number of paddle steps per revolution at both NPL and the University of Liverpool was set to be 359 which is equivalent to 1 degree per step. Fig.2 (c, d) show pictures of the AUTs which are the Schwarzbeck log periodic dipole array antenna 9143 (nominal operating frequency range 300 MHz – 7 GHz; usable frequency 250 MHz – 8 GHz) and the Schwarzbeck 9113 biconical antenna (operating frequency 500 MHz-3 GHz). The VNAs used at NPL and University of Liverpool were R&S ZVB 8 and Keysight N9917A, respectively. Both VNAs were calibrated between 200 MHz and 1200 MHz with 10,001 points. When calculating the impulse responses of the chambers using the IFT, a rectangular window with 100 MHz bandwidth was used. This leads to the total time of 2000 ns and a time resolution of 10 ns in the time-domain. All these parameters are summarised in Table I.

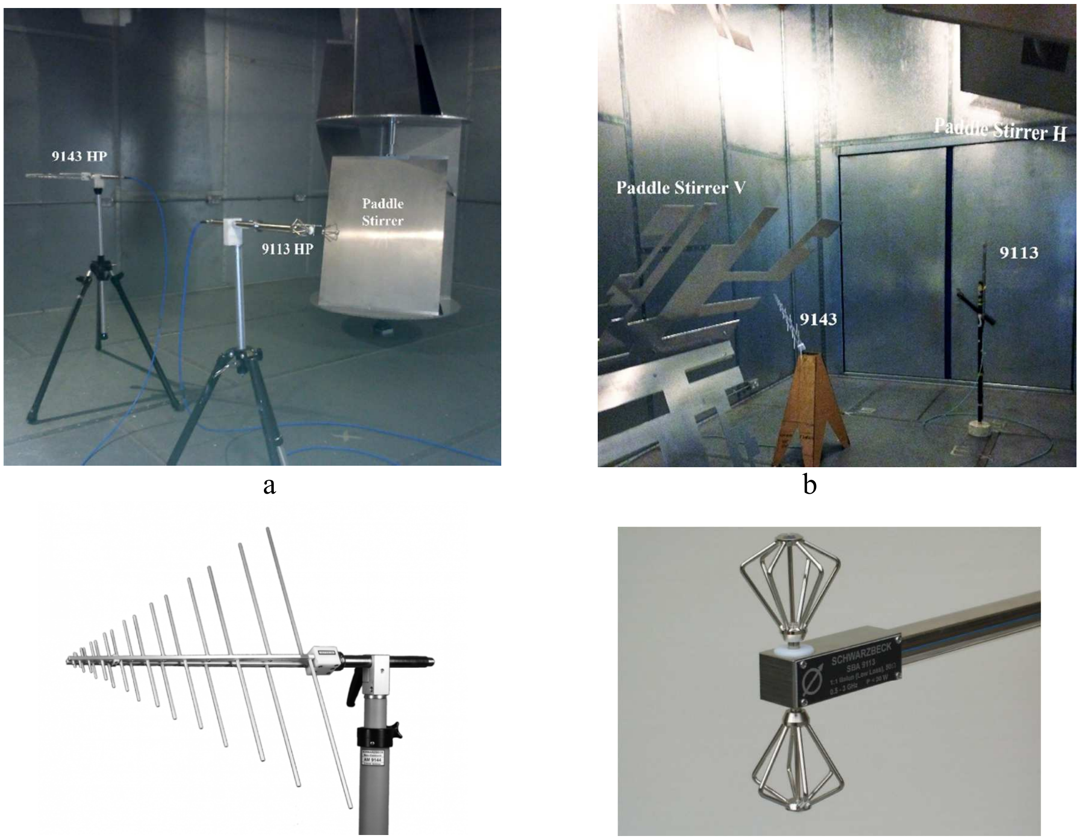


Fig. 2. *Pictures of measurement setups and the AUTs.*
a Test setup in NPL's RC where both antennas were horizontally placed
b Test setup in the University of Liverpool's RC where the endfires of both antennas pointing upwards
c ANT1: the log periodic antenna 9143
d ANT2: the biconical antenna 9113

Table I Summary of parameters used in the study

Parameter	NPL	University of Liverpool
RC Dimensions (m)	6.55 x 5.85 x 3.5	5.8 x 4 x 3.6
No. of Stirrers	1 (vertical)	2 (vertical & horizontal)
VNA	R&S ZVB8	Keysight N9917A
No. of Stirrer Steps per Revolution	359	
Frequency Span (MHz)	200-1200	
No. of Frequency Sampling Points	10001	
Frequency Step (kHz)	100	
IF BW (Hz)	100	
ANT 1	Schwarzbeck Log-periodic 9143 (operating frequency range 250 MHz – 7 GHz)	

ANT 2	Schwarzbeck Biconical 9113 (operating frequency range 500 MHz – 3 GHz)
Frequency Stirring BW (MHz)	20
IFT BW (MHz)	100
Time Resolution (ns)	10

We first compare the electrical characteristics of the two RCs by looking at the Q-factors, decay constants and the enhanced backscatter coefficients. The Q-factors in the time-domain and frequency-domain can be derived using (3). Fig. 3 plots the Q-factors for both RCs in the time- and frequency-domains between 200 MHz and 1200 MHz. One can notice that the time-domain Q-factors are higher than the frequency-domain ones. This is expected as the antenna losses are not taken into account in the time-domain. In addition, the Q-factors of NPL's RC in both domains are mostly higher than those of University of Liverpool. This is because either the size of NPL's RC is larger than that of University of Liverpool's RC or the sum of Ohmic loss and loading (e.g. antenna support) of NPL's RC is less than that of University of Liverpool's RC or a combination of both.

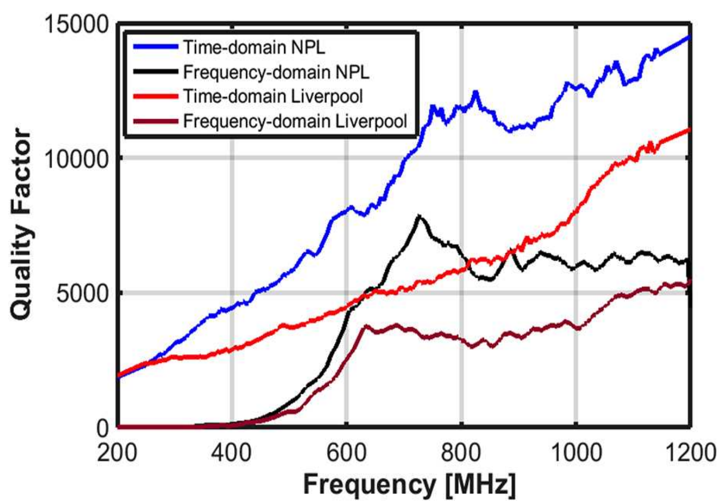


Fig.3. *Q-factors of NPL's RC and University of Liverpool's RC in the time-domain and the frequency-domain.*

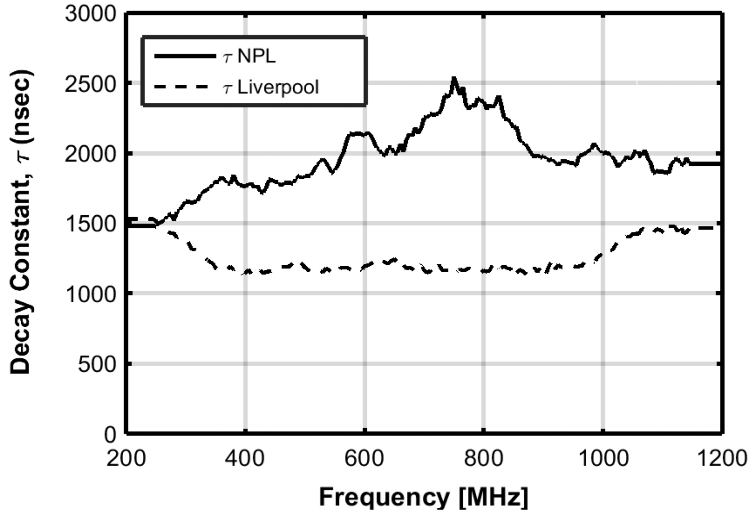


Fig. 4. *Decay constants of the NPL and Liverpool RCs between 200 MHz and 1200 MHz.*

Fig. 4. shows decay constants of the two RCs. The decay constants are calculated using (5-7) with IFT bandwidth of 100 MHz. It can be seen that NPL's RC has higher decay constants than those of University of Liverpool and therefore higher Q-factors which are consistent with Fig. 3.

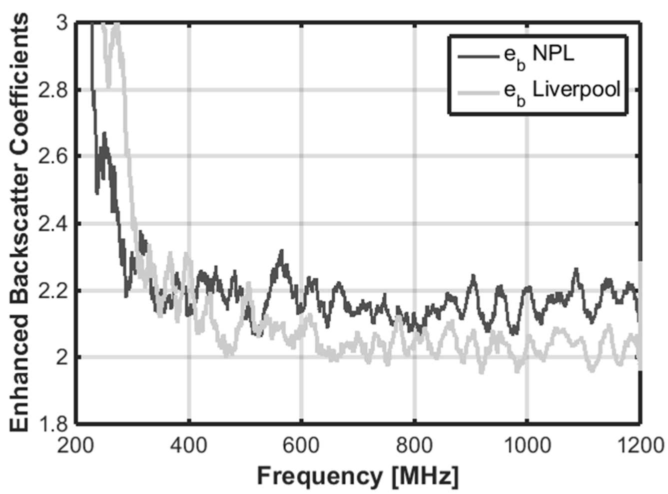


Fig. 5. *The enhanced backscatter coefficients of NPL's and University of Liverpool's RCs.*

We also looked into the enhanced backscatter coefficients of the two RCs in the frequency range between 200 MHz and 1200 MHz. The enhanced backscatter coefficient is used to assess how well an RC is stirred at a particular position within the RC and can be calculated using (9). Fig. 5 shows e_b of both RCs. It is noticed that the field of the University of Liverpool's RC at those locations show a better stirred profile than those in the NPL's RC for frequencies above 400 MHz as its e_b is closer to 2. As discussed in

[14], $e_b = 2$ means that the one-antenna and the two-antenna methods should give similar antenna efficiency.

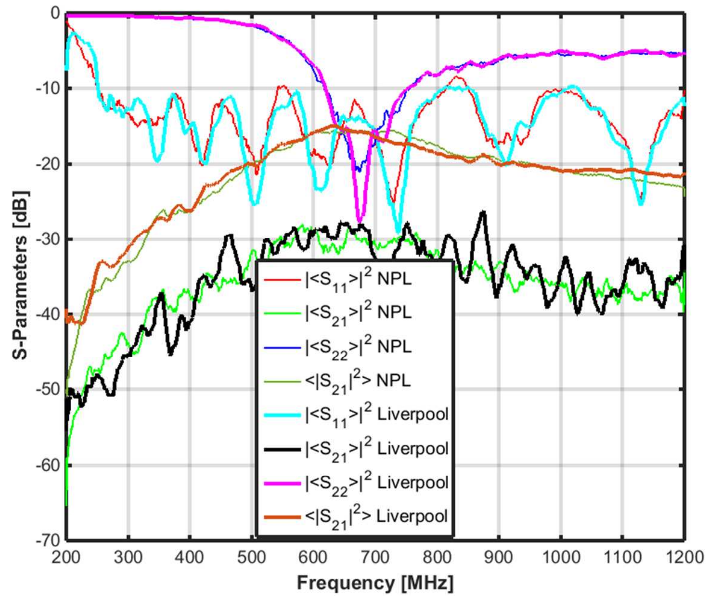


Fig.6 *The unstirred reflection coefficients at antenna's feed ports, transmission coefficients in the two RCs averaged over one revolution and the averaged receiving power. S_{11} and S_{22} refer to antennas 9143 and 9113, respectively.*

We then compared the electrical properties of the AUTs. Fig. 6 compares the unstirred or "free-space" reflection coefficients at the antennas' feed ports and the transmission coefficients between the two antennas in the two RCs. The unstirred *S*-parameters are defined by averaging the S-parameters over all paddle steps, e.g. $10\log\left(\left|\langle S_{11}(n,f)\rangle\right|^2\right)$ for antenna 9143's port reflection coefficient. It can be seen that although two RCs have different mechanical and electrical properties, the measured properties of the antennas agree fairly well. Fig.5. also shows the average received power, i.e. $10\log\left(\left\langle\left|S_{21}(n,f)\right|^2\right\rangle\right)$ measured in the two chambers. The close agreement between the two tests indicates the power losses between the two chambers are similar.

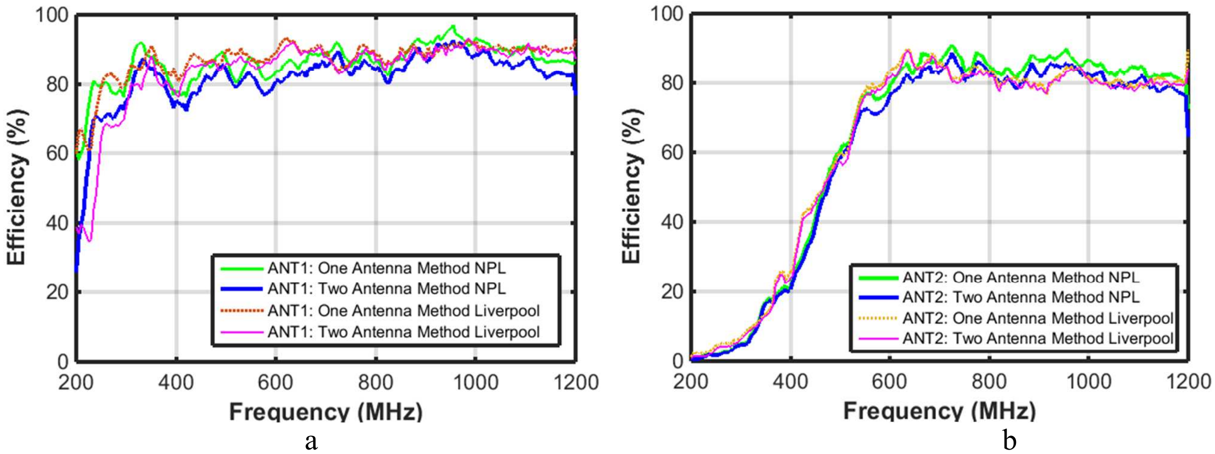


Fig.7. Comparing efficiency of the AUTs obtained by using both one-antenna and two-antenna methods.
a The log-periodic antenna 9143
b The biconical antenna 9113.

Since two antennas were used in the test, we can use the data to work out the efficiency by using both the one-antenna and the two antenna NRA methods. Fig. 7 shows the efficiency of the AUTs obtained by using one-antenna NRA method (8) and two-antenna NRA method (10) along with (11). For antenna 9143 (in Fig. 7a), the University of Liverpool has very close agreement between the results calculated by using both one-antenna and two-antenna NRA methods for frequencies above 300 MHz but NPL's one-antenna and two antenna NRA methods provide relatively larger difference in the efficiency. For both AUTs, NPL's one-antenna NRA method gives slightly higher efficiency than the two-antenna NRA method, but University of Liverpool's two NRA methods agree very well. This is because the enhanced backscatter coefficients of University of Liverpool's RC at the test locations are more close to 2 than those of NPL's RC as already shown in Fig. 5. However, NPL's two-antenna NRA method provides close agreement (<5%) on antenna 9113 (in Fig. 7b) and slightly poorer agreement (10%) on antenna 9143 (in Fig. 7a) with the University of Liverpool's both one-antenna and two-antenna NRA methods.

4. Discussion

In [14] Holloway *et al.* analysed and estimated the uncertainties of the antenna efficiency for one-antenna and two-antenna NRA methods to be around 9%. Further investigations using different antennas, different test times, various antenna positions and different RCs [16-18], showed that antenna efficiency measured using the NRA methods is still within the estimated uncertainty budget. Our results presented in the previous section agree with these findings. However, we note that the effect of the polarisations of the AUTs on the efficiency has not been previously discussed. In [20] it was reported that polarisation imbalance in RCs may be 2-3 dB when analysing the transfer function. By using polarisation stirring, this imbalance can be removed. We therefore wondered if polarisation may also play a role in obtaining the antenna efficiency using the NRA methods.

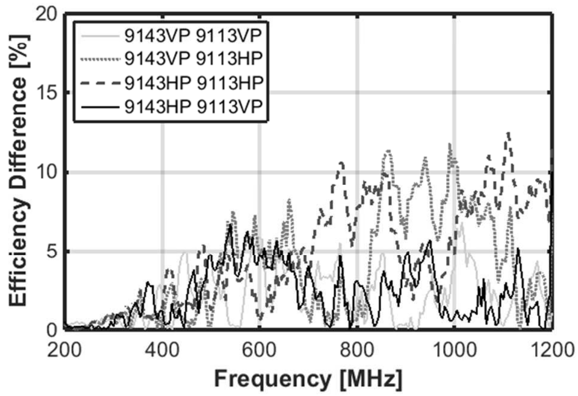
Table 2 Polarisation combinations for the study

Numbering	Polarisation of Antenna 9143	Polarisation of Antenna 9113
1	VP	VP
2	VP	HP
3	HP	HP
4	HP	VP

At NPL we set the same antenna pair with four different polarisation combinations i.e. 9143VP vs 9113VP, 9143VP vs 9113HP, 9143HP vs 9113HP, 9143HP vs 9113VP as shown in Table 2 (where VP denotes vertical polarisation and HP denotes horizontal polarisation) and measured the *S*-parameters following the same procedures as before except that, when using (2), (3b) and (6), averaging was also carried out over the different polarisation combinations. The results are presented in the form of percentage efficiency difference $\Delta\eta$ which is defined as

$$\Delta\eta = \left|\eta_{Pi} - \eta_{Pave}\right| \tag{12}$$

where η_{Pi} $i \in \{1,2,3,4\}$ is the antenna efficiency obtained with each of the different combination of polarisations between the two antennas (as shown in Table 2). η_{Pave} is the efficiency obtained when polarisation stirring (averaging over all four individual polarisations) is applied. One can see from Fig. 8 a and b that the efficiency difference for the biconical antenna 9113 is mostly within 8% for both one-antenna and two- antenna NRA methods. On the other hand, the efficiency difference for the log-periodic antenna 9143 (as shown in Fig. 8 c, d) is mostly within 10%. These results may help to explain the measured results presented in Fig.7. where the directional antenna shows a higher degree of discrepancy than the omni-directional antenna. This is because the antenna polarisation setups at NPL (both antennas horizontally polarised) and at University of Liverpool (the endfires of both antennas pointing upwards) were different, and the efficiency of the log-periodic antenna is more prone to be affected by polarisation than the biconical antenna. The results indicates that polarisation stirring should be implemented if higher accuracy of efficiency is required especially for directional antennas.



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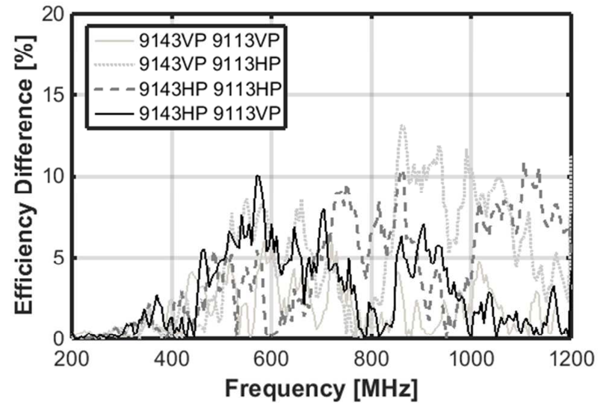

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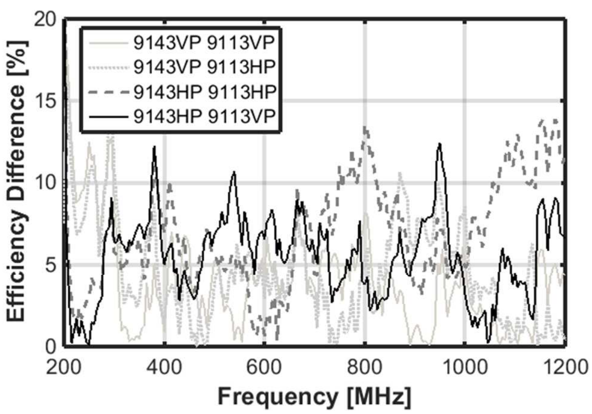

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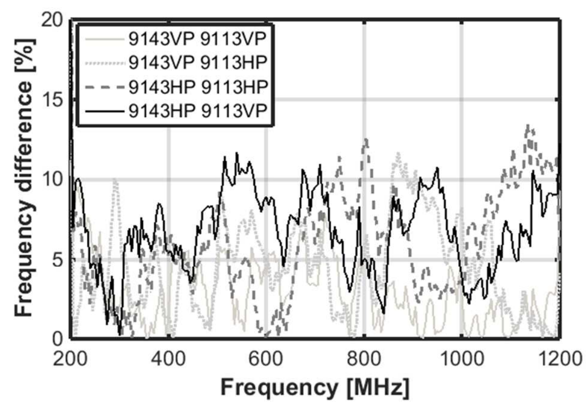

d

Fig. 8. *Comparison of antenna efficiency when polarisation stirring is applied.*
a efficiency difference of antenna 9113 when one-antenna NRA method is used
b efficiency difference of antenna 9113 when two-antenna NRA method is used
c efficiency difference of antenna 9143 when one-antenna NRA method is used
d efficiency difference of antenna 9143 when two-antenna NRA method is used

5. Conclusion

In this paper, we have studied the chamber effects on antenna efficiency measurements using NRA methods and compared antenna radiation efficiency measured in two different RCs (located at NPL and the University of Liverpool) for two different antennas (a directional antenna and an omnidirectional antenna). The antenna efficiency were measured by using two NRA methods namely the one-antenna NRA method and the two-antenna NRA method. It has been found that although the two RCs differ in dimensions and paddle stirrer configuration and hence in Q factors, decay constants and enhanced backscatter coefficients, the discrepancy in the efficiency of the two antennas measured between the two chambers is less than 10% within their operational frequency bands. In particular, the radiation efficiency of the antennas measured using the two-antenna NRA method between the two RCs agrees fairly well with slightly better agreement for the omnidirectional antenna (<5 %) than for the directional antenna (<10 %). In addition, it is also obvious that the effect of non-perfect stirring in the RCs (corresponding to the enhanced backscatter coefficients, e_b being different from 2) is eliminated by the two-antenna NRA method. Further investigation has indicated that polarisation mismatch could lead to up to 8% and 10% discrepancy for the omni-directional antenna and directional log-periodic antenna, respectively. This discrepancy can be removed by performing additional measurements with polarisation stirring. Nevertheless, this study has gained a better understanding of the recently introduced NRA methods and demonstrated the robustness of these methods.

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